SMR/115 - 22

WINTER COLLEGE ON LASERS, ATOMIC AND MOLECULAR PHYSICS

(21 January - 22 March 1985)

LASERS AND THE EPR PARADOX

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IL NUOVO CIMENTO VOL. 78 B, N. 1 11 Novembre 1983

Quantum Mechanics and Faster-Than-Light Communication: Methodological Considerations (*).

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(ricevuto il 27 Aprile 1983; manoscritto revisionato ricevuto l'8 Luglio 1983)

Summary. — A detailed quantum-mechanical analysis of a recent proposal of faster-than-light communication through wave packet reduction is performed. The discussion allows us to focus some methodological problems about critical investigations on physical theories.

PACS. 03.65. – Quantum theory; quantum mechanics.

1. – Introduction.

In this paper, seizing the opportunity of a detailed discussion of some recent proposals of faster-than-light communication through wave packet reduction [1,2], in particular of the « gedanken » experiment suggested in ref. [1], we focus some methodological problems about critical investigations on quantum mechanics and we point out some typical errors of this kind of proposals.

For what concerns these attempts, one could state in general that they are

(*) Work supported in part by Istituto Nazionale di Fisica Nucleare, Sezione di Trieste.
(1) N. HERBERT: *Found. Phys.*, **12**, 1171 (1982).
(2) N. HERBERT: *QUICK—a new superluminal transmission concept*, C-life Report 3753 (April, 1979), unpublished; F. SELLERI: in *Dynamical Systems and Microphysics*, edited by A. BLAQUIERE, F. FER and A. MARZOLLO (Berlin, 1980), p. 393; N. CUFARO-PETRONI, A. GARUCCIO, F. SELLERI and J. P. VIGIER: *C. R. Acad. Sci. Sér. B*, **290**, 111 (1980).

doomed to failure, since it is quite easy to prove [3] that a correct use of quantum-mechanical rules implies that no physical detectable effect whatsoever can be instantaneously induced on a physical system S_1 by interactions or reduction processes suffered by another system S_2 isolated from S_1. These considerations would make unnecessary to proceed to a discussion of papers devoted to superluminal signalling and, therefore, also of ref. [1]. However, there are several reasons for which we think a detailed discussion of that paper is appropriate.

First of all, as already stated, the analysis of the FLASH proposal put forward by HERBERT [1] will offer us the opportunity for a methodological discussion about the various possible critical investigations of the validity of a physical theory.

Secondly, ref. [1] claims to have succeeded « to circumvent the clear-cut prohibitions » of superluminal signalling given in previous papers [3] by widening the notion of observable to include events not explicitly covered by the concept of quantum-mechanical observable. In particular, the author of ref. [1] pretends to have introduced an experimental set-up whose outcomes cannot be accounted for by standard quantum-mechanical rules, since they should not correspond to average values, but to the occurrence of individual events. These statements deserve a detailed analysis to be shown to be unappropriate. Finally, the proposal put forward in ref. [1], by making use of a laser gain tube, raises naturally some questions about the reduction of the noise in amplifiers which are certainly of interest from a practical point of view [4]. This point too deserves a detailed analysis.

In what follows we will make clear, on the one side, the noncorrect argumentation of ref. [1], on the other, the fact that the important result of reducing the noise in a laser devised to duplicate exactly photons of a preassigned polarization is not the crucial point of the problem and that, even if it would be achieved, it would by no means lead to the possibility of faster-than-light signalling. The key point on which the criticism to the Herbert proposal will be based consists in the recognition that his assumptions about the functioning of the laser gain tube lead to a violation of the linear character of quantum mechanics. This point has been independently raised by us [5] and by WOOTTERS and ZUREK [6], who have expressed it in a very clear and concise way. We shall reconsider this argument in detail, since a complete analysis of the proposed experiment has not been done in ref. [6], while its discussion will turn out to be enlightening. In so doing we will also be led to make some general considerations about quantum states of macroscopic bodies.

(3) P. EBERHARD: *Nuovo Cimento B*, **46**, 392 (1978); G. C. GHIRARDI, A. RIMINI and T. WEBER: *Lett. Nuovo Cimento*, **27**, 293 (1980).
(4) See, for example, A. GOZZINI: *Proceedings of the Symposium on Wave-Particle Dualism*, edited by S. DINER, D. FARGUE, G. LOSCHAK and F. SELLERI (Dordrecht, 1983).
(5) Private correspondence with Prof. A. VAN DER MERWE, April 1981.
(6) W. K. WOOTTERS and W. H. ZUREK: *Nature (London)*, **299**, 802 (1982).

2. – Some methodological considerations.

An interesting and essential moment of the scientific activity is the one in which the scientific community, or at least a part of it, feels the necessity of a critical reflection on the conceptual foundations of the theoretical schemes which are (very largely or almost universally) accepted as appropriate for the description of natural phenomena. It goes without saying that such a critical reconsideration of a theory, to be useful, must be carried out with great logical rigour.

Within the possible approaches to a critical analysis of an established theoretical scheme, one can identify three lines which can be followed and which are, in our opinion, perfectly legitimate.

i) One can compare the consequences which can be drawn from an assumed unrestricted validity of the theory under discussion with some general ideas about physical reality and the level of knowledge we can get of it through science, to see whether some contradiction arises. We stress that we consider this a legitimate procedure, even though some scientists could be inclined to consider it as directed to satisfy philosophical instances not relevant to science. The analysis performed by EINSTEIN, PODOLSKY and ROSEN in their famous paper [7] can be interpreted as an example of this line of thought for the case of quantum theory.

ii) One can compare the consequences which can be derived from a *consistent application* of the theory to actually performable or « gedanken » experiments with some general physical principles which are considered as « true » by the scientific community, even though they are not included among the axioms of the considered theory. The various trials [1,2] recently made to prove that the quantum postulates, in particular the wave packet reduction, can lead to faster-than-light communication would fit (were they not wrong in principle) into this line of thought.

iii) One can (and actually one should) check the internal consistency of the theory, showing that no contradiction can arise from the use of all the assumptions on which the theory is based. For example, in the case of quantum mechanics, one follows this line when comparing the assumption that the system-apparatus interaction can be accounted for by quantum mechanics with the postulate of wave packet reduction. This is a crucial problem of the theory and it has been the subject of many deep investigations. In our opinion, however, it has not been yet fully clarified.

(7) A. EINSTEIN, B. PODOLSKY and N. ROSEN: *Phys. Rev.*, **47**, 777 (1935).

3. – EPR paradox and superluminal signalling.

We started our discussion with the distinctions i)-iii), since it allows us to make clear the methodological difference between critical investigations about quantum theory of the EPR type and of the superluminal signalling type. In fact, these latter proposals are essentially attempts to transform a « philosophically » paradoxical situation, pointed out by an analysis of type i), into an explicit contradiction between accepted physical principles, a program which, if successful, would amount to passing to an analysis of type ii). Let us comment on this statement.

The results of the deep analysis performed by EINSTEIN, PODOLSKY and ROSEN (7) can be rephrased (8) by stating that they have pointed out the existence of a contradiction between the assumption of an unrestricted validity of quantum mechanics and the following two general assumptions:

1) the existence of elements of physical reality, in the very precise sense defined in their paper;

2) the impossibility that any action on a system can instantaneously influence the elements of physical reality of another system which is isolated from it.

The EPR argument is extremely important from a conceptual point of view and it points out what at least a part of the scientific community considers a serious difficulty of the theory. The naive possibility of escaping such a difficulty, based on the remark that ordinary quantum mechanics, being a nonrelativistic theory, can very well lead to contradictions with relativity, does not yield a solution to the problem. In fact, on the one side, the instantaneous collapse of the wave function of a composite system is a feature completely independent of the distance of the component subsystems and cannot, therefore, be considered as a nonrelativistic approximation of some process obeying relativistic requirements. On the other side, and this is even more important, the experimentally proved fact that all correlations between the two fragments of a composite system are correctly reproduced by the quantum-mechanical predictions does not leave any space for such a way-out. This situation has been definitively settled up by the recent excellent experimental work of Aspect *et al.* (9). It is useful to stress that the conceptual implications of the results of Aspect's experiment, from the point of view we are following

(8) B. D'ESPAGNAT: *Conceptual Foundation of Quantum Mechanics* (Menlo Park, Cal., 1971).
(9) A. ASPECT, P. GRANGIER and G. ROGER: *Phys. Rev. Lett.*, **47**, 460 (1981); *Phys. Rev. Lett.*, **49**, 91 (1982); A. ASPECT, J. DALIBARD and G. ROGER: *Phys. Rev. Lett.*, **49**, 1804 (1982).

in this paper, are just those illustrated in the above description of the content of the EPR analysis. It is absolutely incorrect to use the tested behaviour of quantum systems to assert that quantum theory implies the possibility of an instantaneous transfer of energy and/or information between spacelike separated observers. In view of the general proofs (2) that one cannot use the wave packet reduction to induce such instantaneous effects, one can state that proposals of this type do not respect the basic requirement of item ii) that the theory under discussion be applied consistently to derive the claimed results.

4. – Analysis of the FLASH proposal.

In order to perform a detailed critical investigation of the proposal put forward in ref. (1), we briefly sketch the essential points of the reasoning developed in that paper. The « gedanken » experiment proposed in ref. (1) can be summarized as follows.

1) One has a quantum system decaying into two photons propagating in opposite directions, the spin state of the system of the two photons being

$$|\psi\rangle = \frac{1}{\sqrt{2}}\{|RL\rangle - |LR\rangle\} = -\frac{i}{\sqrt{2}}\{|HV\rangle - |VH\rangle\}, \tag{4.1}$$

where the first (second) label in a ket describes the polarization of the photon propagating in one direction (in the opposite one). The photon spin states

$$|R\rangle, \quad |L\rangle, \quad |H\rangle = \frac{1}{\sqrt{2}}\{|R\rangle + |L\rangle\}, \quad |V\rangle = -\frac{i}{\sqrt{2}}\{|R\rangle - |L\rangle\}$$

represent circular (right and left) and plane (horizontal and vertical) polarizations, respectively.

2) One observer O measures the polarization states of the photon propagating in one direction. He can choose whether to detect circular or plane polarization, thus inducing, by wave packet reduction, the same type of polarization in the far-away photon propagating in the opposite direction.

3) This photon crosses then an instrument which, according to the author of ref. (1), consists of « a nonselective laser gain tube which multiplies single photons into bursts of identically polarized photons ». Since this sentence is the one containing the crucial assumptions for the argument of ref. (1) and it mixes two different problems, *i.e.* the one of having an apparatus which identically multiplies photons of a fixed polarization and the one of having an apparatus identically multiplying photons of any polarization, it is appropriate to split it into two separate assumptions deserving a completely different analysis:

3*a*) If a photon in the $|R\rangle$ or $|L\rangle$ state crosses the laser gain tube, it gives rise to a state containing a large number n of identical photons with the same polarization, *i.e.* to the states $|nR\rangle \equiv |RR \dots R\rangle$ or $|nL\rangle \equiv |LL \dots L\rangle$, respectively.

3*b*) The laser gain tube does the same when stimulated by a plane polarized photon, so that the emerging state is $|nH\rangle$ or $|nV\rangle$, according to whether the impinging one is $|H\rangle$ or $|V\rangle$, respectively.

4) The emerging beam is then analysed by a beam splitter apparatus plus four (right, left, horizontal and vertical) polarization detectors. The argument goes then as follows: if one denotes by n_R, n_L, n_H and n_V the numbers of photons which are detected by the four analysers, one gets

a) $n_R = n/2$, $n_L = 0$, $n_H = n/4$, $n_V = n/4$ when the incident photon state is $|nR\rangle$,

b) $n_R = 0$, $n_L = n/2$, $n_H = n/4$, $n_V = n/4$ for $|nL\rangle$,

c) $n_R = n/4$, $n_L = n/4$, $n_H = n/2$, $n_V = 0$ for $|nH\rangle$,

d) $n_R = n/4$, $n_L = n/4$, $n_H = 0$, $n_V = n/2$ for $|nV\rangle$.

5) The four different outcomes would then allow the second observer to discover whether the first one has chosen to measure circular or plane polarization, the experimental set-up allowing, therefore, faster-than-light communication between observers.

Let us now investigate critically the above points. The assumptions made under 1) and 2) are perfectly consistent with the quantum formalism. Even the small modifications which would have to be introduced (in principle) in assumption 2), taking into account the impossibility of an ideal measurement of a spin component due to the existence of the additive conservation law of the total angular momentum, can be consistently disregarded, since one can make them arbitrarily small by making the apparatus sufficiently massive.

Let us now come to point 3). The question considered under 3*a*) is surely interesting from a practical point of view [4]. The problem for the specific case under examination is that of investigating whether the assumed functioning of the laser gain tube is not forbidden by the unavoidable noise associated to the randomly polarized spontaneous emission. We do not want to enter into this technical problem. However, we must stress that, from the point of view of the analysis we are performing, the discussion about the possibility of having an apparatus working as assumed under 3*a*) is totally irrelevant. In fact, for what concerns the final-state vectors, the situation which follows from the use of assumption 3*a*) can, in principle, be actually obtained without conflicting in any way with quantum-mechanical rules. To this purpose one can assume that at a given time one is dealing with a system $S_1 + S_2$, where S_1 is a n-photon system and S_2 is any quantum system with internal degrees of freedom. For the system $S_1 + S_2$ one assumes that it is described by the pure state

$$(4.2) \qquad |\psi\rangle = \frac{1}{\sqrt{2}}\{|nR\rangle \otimes |\varphi_1\rangle + |nL\rangle \otimes |\varphi_2\rangle\}$$

(where $|\varphi_1\rangle$ and $|\varphi_2\rangle$ are two orthonormal internal states of system S_2) and that the bunch of n photons and the system S_2 are very far and are propagating in opposite directions. It is obvious that such a state can be very difficult to prepare; however, we stress that, as stated in sect. **2**, to develop a critical analysis of type ii) one can very well resort to « gedanken » experiments, provided they do not violate any quantum-mechanical rule. There is no principle in quantum mechanics which forbids to consider (4.2) as an acceptable state for our system. We will comment further on this point in sect. **5**.

Let us now define two observables $\mathcal{A}$ and $\mathcal{B}$ of system S_2 with the following characteristics: the operator A of the Hilbert space of system S_2 associated to the observable $\mathcal{A}$ has $|\varphi_1\rangle$ and $|\varphi_2\rangle$ as eigenstates belonging to two different eigenvalues. The operator B associated to $\mathcal{B}$ does not commute with A and possesses in the linear manifold spanned by $|\varphi_1\rangle$ and $|\varphi_2\rangle$ two eigenstates $|\chi_1\rangle$ and $|\chi_2\rangle$ having the following expressions:

$$(4.3) \qquad |\chi_1\rangle = \frac{1}{\sqrt{2}}\{|\varphi_1\rangle + |\varphi_2\rangle\}, \qquad |\chi_2\rangle = \frac{1}{\sqrt{2}}\{|\varphi_1\rangle - |\varphi_2\rangle\}$$

belonging to two different eigenvalues. If on the system S_2 a measurement of the observable $\mathcal{A}$ is performed, the wave packet reduction process produces for the photon bunch either the state $|nR\rangle$ or the state $|nL\rangle$, according to the result obtained in the measurement. We can then state that the final state of affairs following the use of 3*a*) can very well be imagined to occur without conflicting with any principle of quantum mechanics.

We come now to point 3*b*). As already observed, this is the basic methodologically incorrect point of ref. [1], implying a violation of quantum rules [5,6]. To show this, let us start by considering for simplicity the physical situation described by (4.2). A measurement on S_2 of the observable $\mathcal{A}$ produces photon states $|nR\rangle$ or $|nL\rangle$, while a measurement of the observable $\mathcal{B}$ (the exact analogous of passing from circular- to plane-polarization detection in Herbert's analysis) produces photon states

$$(4.4) \qquad \frac{1}{\sqrt{2}}\{|nR\rangle + |nL\rangle\} \quad \text{or} \quad \frac{1}{\sqrt{2}}\{|nR\rangle - |nL\rangle\},$$

respectively. These states are by no means the states $|nH\rangle$ and $|nV\rangle$ which would be necessary to perform the further steps 4) and 5) of the Herbert analysis. This makes very clear that point 3*b*) violates a basic requirement of quantum mechanics, *i.e.* its linearity. We have preferred to discuss firstly the «gedanken» experiment based on state (4.2) because it presents all the conceptual features of the Herbert proposal but is simpler to discuss. The argument can be immediately transferred to the FLASH experiment. In this case, however, the discussion is a little bit more involved, since, to be appropriate, it requires the consideration of the states of the laser gain tube after the interaction.

Let us then suppose that there exists a laser gain tube with the following properties: it is initially in a state $|A_0\rangle$ and, when stimulated by a photon in state $|R\rangle(|L\rangle)$, it goes into a state $|A_R\rangle(|A_L\rangle)$ emitting a burst of photons represented by the state $|nR\rangle(|nL\rangle)$. We write then [10]

$$\left\{\begin{array}{l}|A_0\rangle\otimes|R\rangle\rightarrow|A_R\rangle\otimes|nR\rangle\,,\\ |A_0\rangle\otimes|L\rangle\rightarrow|A_L\rangle\otimes|nL\rangle\,.\end{array}\right. \tag{4.5}$$

From linearity we get

$$|A_0\rangle\otimes|H\rangle\rightarrow\frac{1}{\sqrt{2}}\{|A_R\rangle\otimes|nR\rangle+|A_L\rangle\otimes|nL\rangle\}\,, \tag{4.6a}$$

$$|A_0\rangle\otimes|V\rangle\rightarrow\frac{1}{\sqrt{2}}\{|A_R\rangle\otimes|nR\rangle-|A_L\rangle\otimes|nL\rangle\}\,. \tag{4.6b}$$

We note that in all instances, *i.e.* using (4.4) or (4.6), the emerging states involve linear superpositions (with coefficients which are equal in moduli) of the states $|nR\rangle$ and $|nL\rangle$. In no case the final state can be considered to be $|nH\rangle$ or $|nV\rangle$, as done in ref. [1].

The above considerations should have made very clear the error of the argumentation of ref. [1]. Moreover, the consideration of the example based on the use of eq. (4.2) points out that the claimed introduction of a new kind of quantum measurement, emphatically called «third-kind measurement» in Herbert paper, is unimportant (since the situation described under 3*a*) can be in principle assumed to occur) and erroneous (since in no case one can produce states $|nV\rangle$ and $|nH\rangle$ if 3*a*) is occurring).

To completely understand the physical characteristics of the FLASH proposal, it is useful to pursue the discussion of points 4) and 5).

The analysis of point 4) reduces to checking what are the actual responses of the four polarization analysers corresponding to the different quantum states for the many-photon system which are originated by the measurement

(10) We do not want to discuss here the limitations which could be derived for the scheme (4.5) and the information which could be obtained on the states $|A_R\rangle$ and $|A_L\rangle$ by the use of the existence of the additive conservation law of the angular momentum. The argument we are developing depends only on the linear nature of quantum evolution and to reach the desired conclusions we prefer not to use other assumptions, even if they are quite natural.

performed by the first observer. For this purpose we consider, on the one side, the final states $|nR\rangle$ or $|nL\rangle$ (or analogously (4.5)) and, on the other, the states (4.4) (or (4.6)). The problem is then reduced to comparing the numbers n_R, n_L, n_H and n_V of the countings of the four polarization analysers which are obtained when the impinging state contains *only* right-polarized photons or alternatively *only* left-polarized photons (corresponding to the two outcomes of a measurement of $\mathcal{A}$ on S_1, the two alternatives occurring with the same probability) with the numbers obtained from an impinging state which is a *quantum superposition* with coefficients of equal moduli of a state in which *all* photons are right polarized and a state in which *all* photons are left polarized (in our example these latter states are generated by the measurement of $\mathcal{B}$ on S_1).

To see clearly that the statements under 4) about the outcomes of the countings, which should allow the identification of what kind of measurement the first observer has chosen to perform, are wrong, it is sufficient to analyse the countings of n_R and n_L. When the incoming state contains only right-polarized photons (say N of them), if one performs a measurement of circular polarization, one gets obviously that all photons are right polarized, *i.e.*

$$n_R=N\,,\qquad n_L=0\,. \tag{4.7a}$$

Analogously, if in the initial state all photons are left polarized, one gets

$$n_R=0\,,\qquad n_L=N\,. \tag{4.7b}$$

Since the two considered alternatives occur with equal probabilities, we can make the following statement (which is obvious and agrees with the one made in ref. [1]):

When the first observer chooses to measure the observable $\mathcal{A}$ (in Herbert set-up this means to measure circular polarizations), then the outcomes for n_R and n_L are alternatively (4.7*a*) or (4.7*b*), each alternative having the same probability to occur.

Let us come to the other case, in which the first observer chooses to measure the observable $\mathcal{B}$ on S_1 (in Herbert set-up this means to measure linear polarizations). The resulting state for the photon system is then of type (4.4), *i.e.* a linear superposition (with coefficients of equal moduli) of two states, one containing only right-polarized photons and the other the same number of left-polarized photons. The obvious but important fact to be stressed is that such a state, when subjected to a measurement aimed to identify how many photons are right or left polarized, can never give a result in which both right- and left-polarized photons are found (*i.e.* for which both n_R and n_L are different from zero), since such a state has zero projection on all states which contain *both* right- and left-polarized photons. The peculiar structure of states (4.4) implies that, when one photon is found to be right (left) polarized, then all photons turn out to have the same polarization. Therefore, we can make this second statement:

When the first observer chooses to measure the observable $\mathcal{B}$ (in Herbert set-up this means to measure plane polarizations), then the outcomes for n_R and n_L are again (4.7*a*) or (4.7*b*), each alternative occurring with the same probability.

Obviously one can discuss in an analogous way the countings of horizontal and vertical plane polarizations, showing that in all cases one always gets $n_H = n_V$. There follows that the final outcomes of the experiment are always the same and are those listed under items *a*) and *b*) of point 4) of sect. **3**. What the first observer chooses to measure does not change in any way the obtained results for the four counters.

The errors of the analysis of ref. (1) are, therefore, simply consequences of the wrong assumptions about the photon states generated by the different measurements. HERBERT is assuming that in the case of plane-polarization measurements by the first observer one is generating a photon state

$$|nH\rangle = \left(\frac{1}{\sqrt{2}}\right)^N \{(|R\rangle + |L\rangle)_1 \otimes (|R\rangle + |L\rangle)_2 \otimes \ldots \otimes (|R\rangle + |L\rangle)_N\} \tag{4.8}$$

(or the analogous one $|NV\rangle$), which obviously has nonzero projection on states containing both right- and left-polarized photons, and actually leads, for large N, to countings for which $n_R = n_L$ and either n_H or n_V turn out to be zero.

It is important to stress again that assuming (4.8) together with (4.5) means to assume that the laser gain tube violates in its functioning the linear character of quantum mechanics. The whole **FLASH** argument can then be rephrased in this way: ***assuming that quantum mechanics is violated***, then, ***using quantum-mechanical arguments***, one can ***prove*** that quantum mechanics conflicts with basic requirements of relativity. All faster-than-light signalling proposals that we know present this contradictory way of reasoning. A further remark about ref. (1) is appropriate. The author insists repeatedly on the fact that his proposal can escape the (admittedly) correct proofs of the impossibility of faster-than-light signalling by widening the class of observables, *i.e.* introducing something which cannot be described by standard quantum mechanics. The motivation for this would be that quantum theory is only concerned with predictions about average values and not with individual events. In his words «there are many possible ways that individual events can realize the same quantum averages. Quantum theory regards all these ways as equivalent, as indistinguishable outcomes». Our previous analysis should have made very clear the unappropriateness of these remarks. The proposed experiment can be completely and exhaustively analysed within the standard quantum formalism, as we have done, and quantum mechanics is perfectly apt to foresee how many right, left, horizontal and vertical photons will be detected in the «single event» produced by the impinging bunch of photons. Actually, it is just quantum theory, when correctly used, that allows us to assert with absolute certainty that the outcome $n_R = n_L$ cannot be obtained in a single process, even when the first observer measures linear polarizations, and, on the contrary, tells us that the «single events» will always be of type (4.7*a*) or, alternatively, of type (4.7*b*), independently of what the first observer is measuring.

To conclude, we want to stress again firmly that, in our opinion, if one tries to elaborate a critical analysis of type ii) for quantum theory, one certainly has to follow a procedure which *cannot be* the one of proving that the reduction of the wave packet can lead to faster-than-light communication.

5. – Quantum superposition of states of macroscopic bodies.

In this section we want to develop some considerations about linear superpositions of states of macroscopic bodies, suggested quite naturally by the previous discussions, particularly by the consideration of states of the form (4.2) (analogous remarks could be made starting from states (4.6)). As already stated, there is nothing in the principles of quantum mechanics which forbids to consider a state like (4.2) as a possible state for a system $S = S_1 + S_2$, where S_1 is a n-photon system. Due to the assumed very large value of n, the photon system can be considered as a sort of macroscopic system. One could then think of a situation in which, in place of the states $|nR\rangle$ and $|nL\rangle$, one has two distinguishable macroscopic states $|M_1\rangle$ and $|M_2\rangle$ of a macroscopic body. We are then considering the case of a system S, composed of a macroscopic part S_1 and of a microscopic system S_2, prepared in the quantum state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\{|M_1\rangle \otimes |\varphi_1\rangle + |M_2\rangle \otimes |\varphi_2\rangle\}, \tag{5.1}$$

i.e. in a state in which different macroscopic states enter. Suppose then that the microscopic system S_2 is the one already considered in sect. **4**, so that one can measure on it either the observable $\mathcal{A}$ (whose eigenstates are $|\varphi_1\rangle$ and $|\varphi_2\rangle$) or the observable $\mathcal{B}$ (with eigenvectors $|\chi_1\rangle$ and $|\chi_2\rangle$). According to the wave packet reduction, by a measurement on S_2 one forces the system S_1 in a state which is either $|M_1\rangle$ (or $|M_2\rangle$) when $\mathcal{A}$ is measured, or

$$|M_+\rangle = \frac{1}{\sqrt{2}}\{|M_1\rangle + |M_2\rangle\} \qquad \left(\text{or} \quad |M_-\rangle = \frac{1}{\sqrt{2}}\{|M_1\rangle - |M_2\rangle\}\right)$$

when $\mathcal{B}$ is measured. The above considerations imply that, if a state like (4.2) could actually be prepared and if wave packet reduction occurs, one would have at his disposal a simple mechanism to produce quantum superpositions of macroscopically different states ([11]). In such a case the phase relations between the two states entering the superposition are significant. Obviously, this does not imply that measurements performed on the macroscopic body would allow us to understand whether the far-away observer has chosen to measure $\mathcal{A}$ or $\mathcal{B}$; however, the fact that the phase relations of $|M_1\rangle$ and $|M_2\rangle$ are important means that the algebra of the observables of the macroscopic body is non-Abelian. As is well known, the consideration of macro-objects on which noncommuting observables can be measured is the main source of the difficulties of the quantum theory of measurement. Thus the previous discussion leads us back to the problem of the internal consistency of the theory we have already mentioned under iii) in sect. **2**.

Concluding, our analysis should have clarified that in any case the real problem under discussion is that of being able to prepare states like (4.2) or (4.6): but this is nothing else than the basic problem of the Von Neumann chain and of the level at which it can be broken.

([11]) It can be useful to note also that the possible states generated by the measurement of $\mathcal{B}$ on S_2 possess a sort of extreme « instability » *vs.* any measurement process. In fact, if, *e.g.*, we consider the case of states of systems with aligned spins, even though these states may describe an enormous number of constituent systems (in the case of a macroscopic body of the order of the Avogadro number), it is sufficient to make a spin measurement on one single constituent to induce a « jump » of the whole system into one of the « stable » states $|M_1\rangle$ or $|M_2\rangle$.

● RIASSUNTO

In questo lavoro si fa un'accurata analisi in termini di meccanica quantistica di una recente proposta di trasmissione di segnali a velocità maggiore di quella della luce per mezzo del meccanismo di riduzione del pacchetto d'onde. La discussione permette di puntualizzare il contenuto metodologico delle analisi critiche delle teorie fisiche.

Квантовая механика и связь « быстрее скорости света »: методологические рассмотрения.

Резюме (*). — В этой работе проводится подробный квантовомеханический анализ недавнего предложения передачи сигналов быстрее скорости света посредством преобразования волнового пакета. Обсуждение позволяет выделить методологические проблемы критических исследований физических теорий.

(*) *Переведено редакцией.*